Intra-strand resistance and current transfer length in multi-filamentary NbTi, Nb₃Sn, MgB₂, BSSCO and ReBCO conductors

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Motivation

- Aim: (extensive) database for intra-strand/tape resistances of multi-filamentary NbTi, Nb$_3$Sn, MgB$_2$, BSSCO and ReBCO superconductors

- To quantify the impact of locally varying strain conditions, filament fracture and current (re-)distribution process between matrix and superconducting filaments occurring at current injection points in relation to strand internal architecture

- Modeling transport properties of strain sensitive Nb$_3$Sn strand under load and scaling to full size CICCs subjected to large EM forces

High strain (low $I_c$) due to bending ➔ Current transfer among filaments (cracks & strain variations)

Current transfer length
Intra Strand Resistance characteristics

Superconducting wires/tapes: NbTi, Nb$_3$Sn, MgB$_2$, Bi2212, Bi2223 and ReBCO

Number of filaments: from 1 – 14,040

Diameter of filaments: from 2.6 - 160 μm

Matrix: Cu, bronze, Ag, Nb
Experimental setup: intra-strand resistance

- Direct measurement of inter-filament resistance and overall potential distribution across the transverse cross-section of thin strand ‘slices’ (double polishing).
- 4 micro-needles are positioned anywhere in the cross section, serving as voltage taps and current leads for 4-point V-I measurements.

Experimental setup: current transfer length

- Current transfer length is determined by the matrix-to-filament resistance, matrix resistance, and geometry of cross-section.

- Copper potential tips (diameter of 50 µm) on the sample by spot-welding to monitor the potential distribution along the sample length.

- The current is injected and distributed equally at the outer shell.
Model: intra-wire resistance

Matrix resistivity (RRR, EDX for bronze)
Cross-sectional layout (Microscopy)

Independent experiments

Filament-to-matrix contact resistivity

Unknown parameter to be solved

Model Output

Matching with experiment

Transverse resistance

COMSOL Model

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Filament-to-matrix contact resistivity

Overview of the filament-to-matrix contact resistivity $R_\square$ ($\Omega m^2$):

- **NbTi**: $\sim 5 \times 10^{-15}$
- **Nb$_3$Sn**: $1 \times 10^{-15} \sim 10^{-14}$
- **MgB$_2$**: $\sim 1 - 6 \times 10^{-12}$
- **BSCCO**: $\sim 3 \times 10^{-14} - 2 \times 10^{-13}$
- **ReBCO**: $\sim 1 \times 10^{-14}$

Surprisingly 2 to 3 orders higher than commonly measured (indirect method) for example in NbTi or Nb$_3$Sn wires.

- Inter-metallic layers
- Porosity

Results: current transfer length

- Experimental results for Nb$_3$Sn bronze wire with thousands of filaments and high resistive matrix in the filamentary zone

- Note the “classical” current transfer model predicts the current in the matrix to decay exponentially with the distance to the current lead.
- Instead, a distinct upward curvature is noticeable.
Results: current transfer length

- Dependences of magnetic field and transport current vs. distance away from current joint
- Layer by layer penetration
- Magneto-resistivity

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• A three-layer analytical model is proposed.

• A saturated filamentary ring with increasing thickness along with the injected current is introduced.

• The effective current transfer length scale $\lambda_{\text{eff}}$ adds the influence of the high resistive matrix layer into the 1D ‘classical’ model.

$$I_{sc}(x) = I_{in} \left(1 - \exp\left(-\frac{x}{\lambda}\right)\right)$$

$$\lambda_{\text{eff}} = \sqrt{\frac{R_{\text{eff}} \cdot h_{ms}}{\rho_{ms}}} = \sqrt{\frac{(R_{\square} + \rho_{tf} h_{tf}) \cdot h_{ms}}{\rho_{ms}}} = \sqrt{\lambda_{0}^2 + \frac{\rho_{tf} h_{tf} h_{ms}}{\rho_{ms}}}$$

$$\lambda_{0} = \sqrt{\frac{R_{\square} \cdot h_{ms}}{\rho_{ms}}}$$

$$R_{\text{eff}} = R_{\square} + \rho_{tf} h_{tf}$$

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3D Strand Model: current transfer length

- Strand modelled by a 3D resistive network of matrix elements and filaments.
- Filament-to-matrix contact resistance $R_{fm}$ ($\Omega m^2$)
- Transverse coupling resistance between matrix elements.
- Filament resistance is given by power law with $I_c$ and $n$-value

- Input resistive parameters are the measured intra-strand resistances
- Superconducting filament parameters: $I_c$ and $n$-value
- Boundary condition: the injected current is distributed to the matrix (Cu) in the outer ring.


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A good agreement between strand model prediction and experimental data validates the measured and extracted intra-strand resistance from direct measurements.

The deviations in the analytical model predictions: increasing with distance, highly likely caused by the difference for the wire shape (a multi-layered block vs circle).
Summary

- For the first time a systematic study of the intra-wire/tape resistance (direct method) with a wide range of superconductors has been performed.
- The values of filament-to-matrix contact resistivity are mostly in the range of $1 \times 10^{-15} \sim 10^{-14} \ \Omega m^2$, but for MgB$_2$ wire 2 or 3 orders higher is found.
- The extracted parameters give a better insight in the current flow patterns, and allow a quantitative description of the current redistribution process inside strands.
- Extensive database available for further exploration of correlations between strand performance (coupling losses, current transfer length, ...) and strand architecture (materials and layout, crack pattern,...)